Canopy water content retrieval from hyperspectral remote sensing

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Abstract: Biogeochemical processes in plants, such as photosynthesis, evaporation and net primary production, are directly related to foliar water. Therefore, canopy water content is important for the understanding of the terrestrial ecosystem functioning. Spectral information related to the water absorption features at 970 nm and 1200 nm offers possibilities for deriving information on leaf and canopy water content. Hyperspectral reflectance data representing a range of canopies were simulated at the leaf level using the PROSPECT model and at the canopy level using the combined PROSPECT+SAILH model. The simulations were in particular used to study the spectral information related to the water absorption features at about 970 nm and 1200 nm. At the leaf level this information was related to the leaf water content. At the canopy level this information was related to the leaf area index (LAI) and the canopy water content (CWC). In particular derivative spectra close to these absorption features showed a strong predictive power for the leaf and canopy water content. Ratio indices defining the absorption features had a smaller predictive power. The feasibility of using information from the water absorption features in the near-infrared (NIR) region of the spectrum was tested by estimating canopy water content for two test sites with different canopy structure. The first site was a homogeneously managed agricultural field with a grass/clover mixture and with very little variation within the field, being part of the Droevendaal experimental farm at Wageningen, the Netherlands. The other site was a heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. Spectral information at both test sites was obtained with an ASD FieldSpec spectrometer during the summer of 2004 and 2005, respectively. Individual spectral bands and traditional vegetation indices based on red and NIR spectral bands yielded moderate estimates for CWC. Ratio indices describing the absorption features clearly yielded better results. Best results were obtained for the derivative spectra. Highest correlation with CWC was obtained for the derivative spectrum at the slopes of the first water absorption feature. However, here absorption by atmospheric water vapour also should be taken into account, yielding a preference for the right shoulder at about 1040 nm.

CANOPY WATER CONTENT RETRIEVAL FROM HYPERSPECTRAL REMOTE SENSING

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ABSTRACT:

Biogeochemical processes in plants, such as photosynthesis, evaporation and net primary production, are directly related to foliar water. Therefore, canopy water content is important for the understanding of the terrestrial ecosystem functioning. Spectral information related to the water absorption features at 970 nm and 1200 nm offers possibilities for deriving information on leaf and canopy water content.
Hyperspectral reflectance data representing a range of canopies were simulated at the leaf level using the PROSPECT model and at the canopy level using the combined PROSPECT+SAILH model. The simulations were in particular used to study the spectral information related to the water absorption features at about 970 nm and 1200 nm. At the leaf level this information was related to the leaf water content. At the canopy level this information was related to the leaf area index (LAI) and the canopy water content (CWC). In particular derivative spectra close to these absorption features showed a strong predictive power for the leaf and canopy water content. Ratio indices defining the absorption features had a smaller predictive power.
The feasibility of using information from the water absorption features in the near-infrared (NIR) region of the spectrum was tested by estimating canopy water content for two test sites with different canopy structure. The first site was a homogeneously managed agricultural field with a grass/clover mixture and with very little variation within the field, being part of the Droevendaal experimental farm at Wageningen, the Netherlands. The other site was a heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. Spectral information at both test sites was obtained with an ASD FieldSpec spectrometer during the summer of 2004 and 2005, respectively.
Individual spectral bands and traditional vegetation indices based on red and NIR spectral bands yielded moderate estimates for CWC. Ratio indices describing the absorption features clearly yielded better results. Best results were obtained for the derivative spectra. Highest correlation with CWC was obtained for the derivative spectrum at the slopes of the first water absorption feature. However, here absorption by atmospheric water vapour also should be taken into account, yielding a preference for the right shoulder at about 1040 nm.

1. INTRODUCTION

The canopy water content, being the difference between fresh and dry matter weight, is of interest in many applications. Biogeochemical processes, such as photosynthesis, evaporation and net primary production, are directly related to foliar water and are moreover commonly limited by water stress. Thus, canopy water content is important for the understanding of the terrestrial ecosystem functioning (Running and Coughlan, 1988).

Water absorption features for liquid water can be found at approximately 970, 1200, 1450 and 1950 nm (Curran, 1989). The features at 1450 and 1950 nm are most pronounced. However, at about 1400 and 1900 nm also broad absorption features occur due to water vapour in the atmosphere. As a result, hardly any radiation is reaching the Earth's surface and, thus, the liquid water bands at 1450 and 1950 nm cannot be used. The features at 970 and 1200 nm are not that pronounced, but still clearly observable (Danson *et al*., 1992; Sims and Gamon, 2003). Therefore, these offer interesting possibilities for deriving information on leaf and canopy water content. However, in these regions also minor absorption features due to atmospheric water vapour occur at 940 and 1140 nm (Iqbal, 1983). These are shifted somewhat to shorter wavelengths in comparison to the liquid water bands caused by water in the canopy. Figure 1 illustrates the position of the liquid water absorption features in the near-infrared (NIR) region for some spectral measurements on grassland plots.

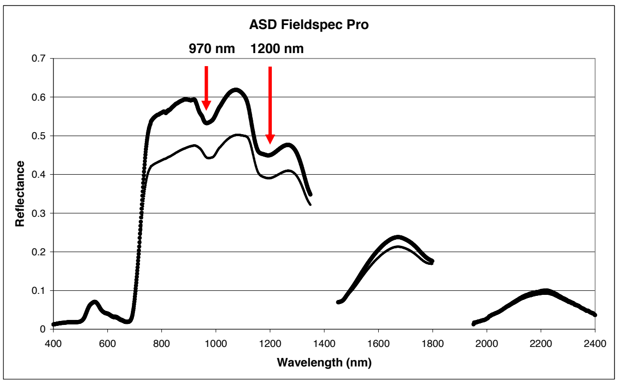

Figure 1. Example of two spectral signatures of grassland plots measured with the ASD FieldSpec Pro. The position of the water absorption features at 970 nm and 1200 nm are indicated.

At the leaf level use is often made of the leaf water content in terms of the so-called equivalent water thickness (EWT), defined as the quantity of water per unit leaf area in $g.cm^{-2}$. At the canopy level the canopy water content (CWC) can be defined as the quantity of water per unit area of ground surface and thus is given in $g.m^{-2}$:

$$CWC = LAI \times EWT \tag{1}$$

Thus far, a limited number of studies have developed spectral indices using the water absorption bands at 970 and 1200 nm for estimation of canopy water content. Danson *et al.* (1992) showed that the first derivative of the reflectance spectrum corresponding to the slopes of the absorption feature provides better correlations with leaf water content than those obtained from the direct correlation with reflectance. This was confirmed by Clevers and Kooistra (2006).

Peñuelas *et al.* (1993) focused on the 950-970 nm region and defined the so-called water band index (WI):

$$WI = \frac{R_{900}}{R_{970}}, \tag{2}$$

where R_{900} and R_{970} are the spectral reflectances at 900 and 970 nm, respectively.

Gao (1996) defined the normalised difference water index (NDWI) as:

$$NDWI = \frac{(R_{860} - R_{1240})}{(R_{860} + R_{1240})}, \tag{3}$$

where R_{860} and R_{1240} are the spectral reflectances at 860 and 1240 nm, respectively.

Finally, a continuum removal approach can be applied to the two absorption features at about 970 and 1200 nm. This is a way of normalizing the reflectance spectra (Kokaly and Clark, 1999). Subsequently, the band depth is calculated for each wavelength by calculating one minus the continuum removed spectra. From this spectral band depth, Curran et al. (2001) defined the maximum band depth, the area under the curve, and the maximum band depth normalised to the area of the absorption feature. Malenovský et al. (2006) used the area under the curve normalised by the maximum band depth (ANMB) as an alternative index.

The objective of the present study is to compare different vegetation indices based on the water absorption features at 970 and 1200 nm in estimating the canopy water content. First, model simulations using the PROSPECT and SAILH radiative transfer models were used for studying the relationship between indices and leaf and canopy water content. Subsequently, field spectro-radiometer measurements obtained from two study sites (a cultivated grassland area and a natural area) were analysed.

2. MATERIAL AND METHODS

2.1 Study Sites and Field Data

The first study site concerns a grassland field with a mixture of grass and white clover at the 'Droevendaal' experimental farm in Wageningen, the Netherlands. A total of 20 plots were defined within a 2.2 ha field. Plots were each 15 m long and 3 m wide and they were harvested using a plot-harvester on July 30th, 2004. Biomass (fresh weight) was determined with a built-in weighing unit on the harvester. Samples of the harvested material were oven dried for 72 hours at 70°C and dry matter weight as well as canopy water content was determined.

The second study site is a very heterogeneous natural area in the floodplain Millingerwaard along the river Waal in the Netherlands. This is a nature rehabilitation area, meaning that individual floodplains are taken out of agricultural production and are allowed to undergo natural succession. This has resulted in a heterogeneous landscape with river dunes along the river, a large softwood forest in the eastern part along the winter dike and in the intermediate area a mosaic pattern of different succession stages (pioneer, grassland, shrubs). Nature management (e.g., grazing) within the floodplain is aiming at improvement of biodiversity. Based on the available vegetation map of the area, 12 locations with specific vegetation structure types were selected. For each location a plot of 20 x 20 m was selected with a relatively homogeneous vegetation cover. End of June 2005 vegetation fresh biomass was sampled in three subplots per plot measuring 0.5 x 0.5 m. After drying for 24 hours at 70°C, vegetation dry matter weight and canopy water content were determined. Subsequently, the average canopy water content per plot was calculated.

2.2 Field Spectroradiometer Measurements

July 29th, 2004, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at site 1 (Wageningen). The spectroradiometer was deployed using a fiber optic cable with a 25° field of view. Measurement height above the plot was about 1 – 1.5 m. As a result, the field of view at the plot level was circular with a radius ranging from 0.22 – 0.33 m. About 10 measurements per plot were performed, whereby each measurement represents the average of 50 readings at the same spot. The sampling interval was 1 nm. Calibration was done by using a Spectralon white reference panel.

June 19th, 2005, a field campaign with an ASD FieldSpec Pro FR spectroradiometer was performed at site 2 (Millingerwaard). For every plot 12 measurements were performed according to the VALERI (VAlidation of Land European Remote sensing Instruments) sampling scheme (Morisette *et al*., 2006), whereby each measurement was the average of 15 readings at the same spot. Measurement height was about 1 m above the vegetation. A Spectralon white reference panel was used for calibration.

After calculating average spectra per plot, the resulting spectra were smoothed using a 15 nm wide moving Savitsky-Golay filter (applying a second order polynomial fit within the window) to reduce instrument noise.

2.3 Reflectance Models

The PROSPECT model is a radiative transfer model for individual leaves (Jacquemoud and Baret, 1990). It simulates leaf spectral reflectance and leaf spectral transmittance as a function of leaf chlorophyll content (C_{ab}), equivalent leaf water thickness (EWT) and a leaf structure parameter (N). The most recent version of PROSPECT was used including leaf dry matter (C_m) as a simplification for the leaf biochemistry (protein, cellulose, lignin).

The one-layer SAILH radiative transfer model (Verhoef, 1984) simulates canopy reflectance as a function of canopy parameters (leaf reflectance and transmittance, leaf area index and leaf inclination angle distribution), soil reflectance, ratio diffuse/direct irradiation and solar/view geometry (solar zenith angle, zenith view angle and sun-view azimuth angle). It was modified by taking the hot spot effect into account (Kuusk, 1991).

The output of the PROSPECT model can be used directly as input into the SAIL model. As a result, these models can be used as a combined PROSPECT-SAILH model. Simulations were performed at a 5 nm spectral sampling interval. Since the absorption features of leaf constituents are implemented in the PROSPECT model by means of look-up tables and not as continuous functions, simulated spectra have to be smoothed for calculating useful derivatives. Therefore, the simulated spectra were smoothed using a 15 nm wide moving Savitsky-Golay filter (applying a second order polynomial fit within the window).

The inputs for the PROSPECT simulations are shown in Table 1 and those for the combined PROSPECT-SAILH simulations are shown in Table 2.

PROSPECT parameters	Nominal values and range
Equivalent water thickness (EWT)	0.01 – 0.10 $g.cm^{-2}$ (step of 0.01)
Dry matter (C_m)	0.005 / 0.010 / 0.015 $g.cm^{-2}$
Structural parameter (*N*)	1.0 – 2.0 (steps of 0.25)
Chlorophyll a+b (C_{ab})	40 $\mu g.cm^{-2}$

Table 1. Nominal values and range of parameters used for the leaf simulations with PROSPECT

SAILH parameters	Nominal values and range
Equivalent water thickness (EWT)	0.01 – 0.10 $g.cm^{-2}$ (step of 0.01)
Dry matter (C_m)	0.005 $g.cm^{-2}$
Structural parameter (*N*)	1.0 / 1.8 / 2.5
Chlorophyll a+b (C_{ab})	40 $\mu g.cm^{-2}$
Leaf area index	0.5/ 1.0 / 1.5 / 2 / 3 / 4 / 5 / 6
Leaf angle distribution	Spherical / Planophile / Erectophile
Hot-spot parameter	0 / 0.1
Soil reflectance	0.0 / 0.1 / 0.2
Diffuse/direct radiation	0
Solar zenith angle	15° / 30° / 45°
Viewing angle	-30° / 0° / 30°
Sun-view azimuth angle	0°

Table 2. Nominal values and range of parameters used for the canopy simulations with the combined PROSPECT-SAILH model

3. RESULTS AND DISCUSSION

3.1 Simulations PROSPECT Leaf Reflectance Model

Clevers and Kooistra (2006) showed before with PROSPECT model simulations that the leaf dry matter content and particularly the leaf structural parameter have a huge effect on the relationship between the spectral reflectance in the 900 – 1300 nm range and the equivalent water thickness (EWT). Due to this, individual spectral bands are not well correlated with EWT. However, when calculating the first derivative spectra correlations increase significantly. The derivatives at spectral regions close to the water absorption features at 970 and 1200 nm are mainly depending on the EWT and are hardly affected by the leaf structural parameter and the leaf dry matter content. As an example, Figure 2 shows the relationship between the derivative at 942.5 nm and EWT. The wavelength 942.5 nm is at the left shoulder of the 970 nm absorption feature. Good results were also obtained using derivatives at the right shoulder of this feature and at the left shoulder of the 1200 nm absorption feature. Figure 3 illustrates the relationship between the water band index (WI) and EWT. Results for the WI were better than those for the NDWI or for the indices based on the continuum removal method (results not shown). Best results were obtained for the first derivative (R^2 of 0.96 at 942.5 nm).

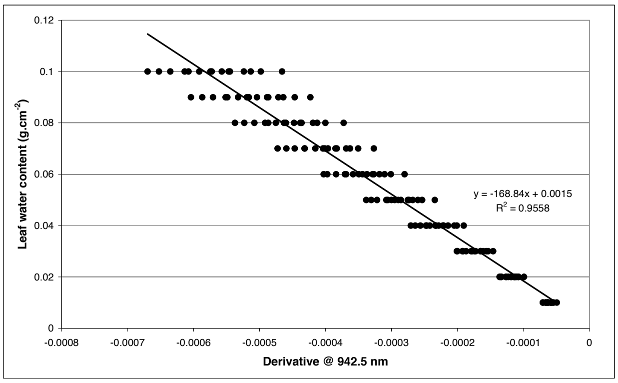

Figure 2. Relationship between first derivative of leaf reflectance at 942.5 nm and equivalent water thickness (PROSPECT simulations with various C_m and *N* values, cf. Table 1)

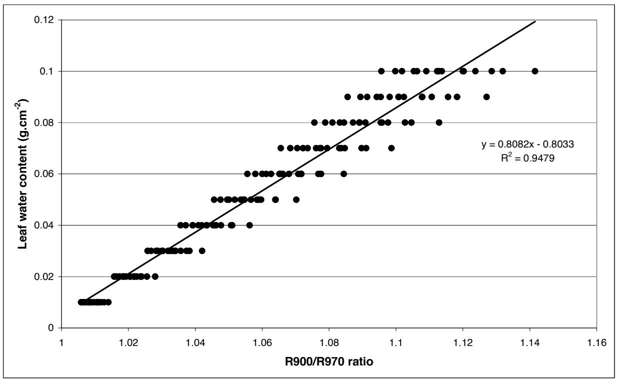

Figure 3. Relationship between the water band index and equivalent water thickness (PROSPECT simulations with various C_m and *N* values, cf. Table 1)

3.2 Simulations SAILH Canopy Reflectance Model

At the canopy level Clevers and Kooistra (2006) showed before that individual spectral bands in the 900 – 1300 nm range are not well correlated with the canopy water content (CWC) using simulations with the combined PROSPECT-SAILH model. However, the first derivative is much better correlated with CWC. High correlations are obtained at the shoulders of the water absorption features. The same regions with high coefficients of determination can be observed as at the leaf level. The effect of variables other than the leaf water content and the LAI are minimised by using the derivative spectra. As an example, Figure 4 shows the relationship between the first derivative at 942.5 nm and CWC for varying leaf angle distribution functions. Again the first derivative showed better results than the afore mentioned indices from literature. The best one of these again is the WI, which is illustrated in Figure 5. The first derivative also yielded stable results for various illumination-viewing combinations. As an example, Figure 6 shows the relationship between the first derivative at 942.5 nm and CWC for nadir viewing, viewing into the hotspot and, opposite to this, viewing into the coldspot. The same relationship is obtained as for the varying leaf angle distributions in Figure 4. For comparison the result for the WI is illustrated in Figure 7, which again shows more scattering due to the varying observation geometry.

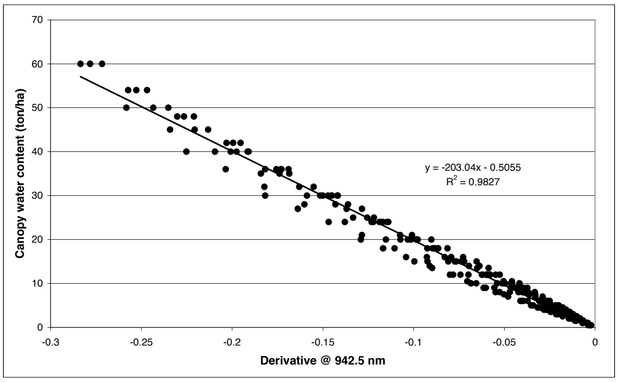

Figure 4. Relationship between first derivative of leaf reflectance at 942.5 nm and canopy water content (PROSPECT-SAILH simulations with various leaf angle distributions, cf. Table 2)

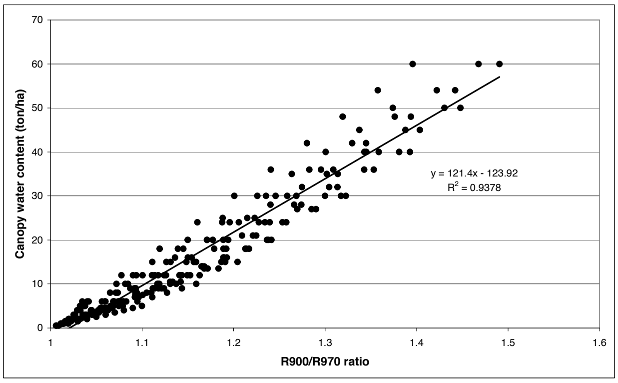

Figure 5. Relationship between the water band index and canopy water content (PROSPECT-SAILH simulations with various leaf angle distributions, cf. Table 2)

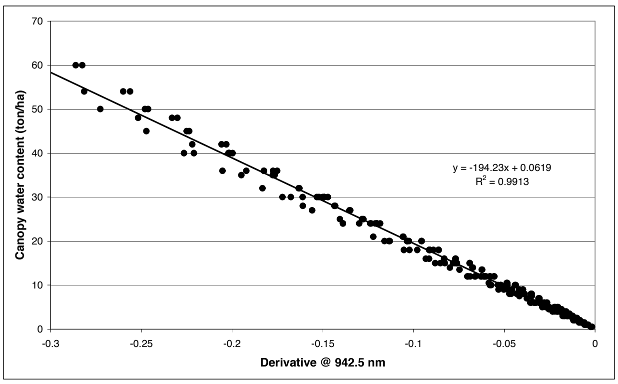

Figure 6. Relationship between first derivative of leaf reflectance at 942.5 nm and canopy water content (PROSPECT-SAILH simulations in nadir, hotspot and coldspot, cf. Table 2)

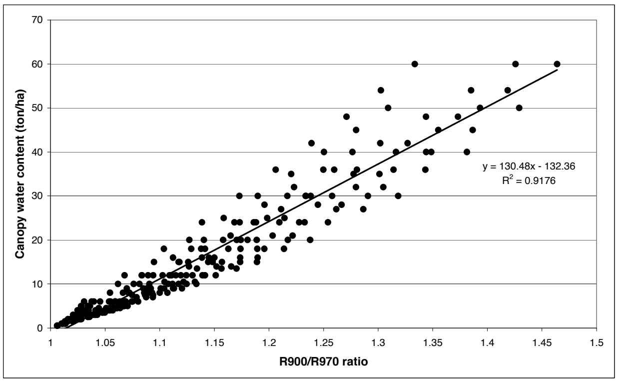

Figure 7. Relationship between the water band index and canopy water content (PROSPECT-SAILH simulations in nadir, hotspot and coldspot, cf. Table 2)

3.3 Test site 1: Wageningen

Using the field spectroradiometer measurements obtained in 2004 at the Wageningen test site, we also found a better relationship between the first derivative at the shoulders of the water absorption features and the canopy water content than between individual spectral bands in the 900 – 1300 nm region and the CWC. For consistency, Figure 8 shows the relationship between the first derivative at 942.5 nm and CWC, although some other derivatives near to 942.5 nm gave slightly better R^2 values. At 942.5 nm an R^2 value of 0.71 was found, whereas at 950.5 nm we found the maximum R^2 value of 0.80. So, we see that the R^2 varies strongly with wavelength for this data set. When Figure 8 is scaled in the same way as Figure 4, we see that the simulated relationship fits very well with the one given in Figure 8. The ratio-based water band indices and the indices based on the continuum-removal method perform worse than the first derivative, but better than the individual spectral bands. Figure 9 illustrates the results for the WI, yielding an R^2 value of 0.26.

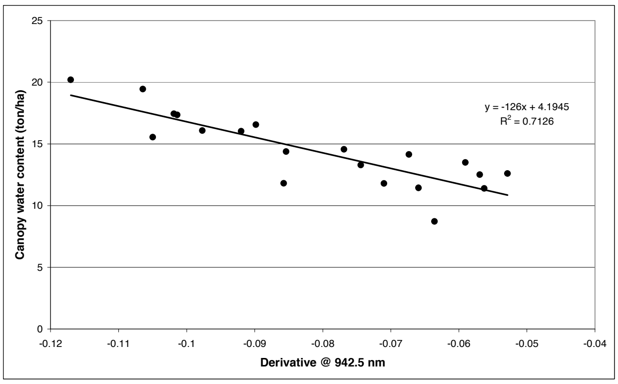

Figure 8. Relationship between first derivative of canopy reflectance at 942.5 nm and canopy water content at the Wageningen test site

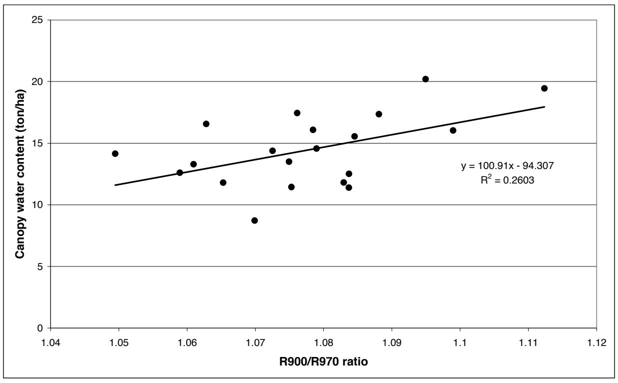

Figure 9. Relationship between the water band index and canopy water content at the Wageningen test site

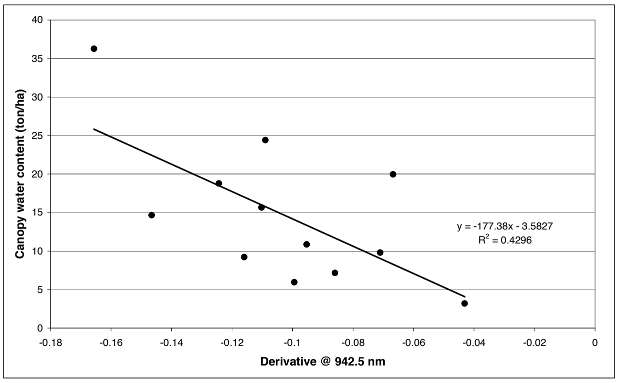

Figure 10. Relationship between first derivative of canopy reflectance at 942.5 nm and canopy water content at the Millingerwaard test site

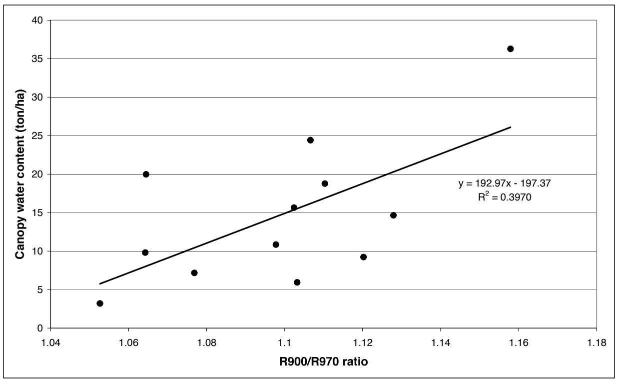

Figure 11. Relationship between the water band index and canopy water content at the Millingerwaard test site

3.4 Test site 2: Millingerwaard

For the Millingerwaard test site in 2005 both field spectroradiometer measurements and canopy water content were obtained. Direct regressions of CWC on individual spectral bands obtained from the field spectroradiometer yielded poor results. R^2 values for the first derivative spectra yielded better results, although R^2 values were not really high for this heterogeneous vegetation site. Figure 10 illustrates the relationship between the first derivative at 942.5 nm and CWC, whereas Figure 11 shows the result for the WI, again being the best water band index. For this data set the first derivative at 1266.5 nm yielded the highest correlation with CWC (R^2 of 0.60). This lies at the right shoulder of the 1200 nm absorption feature. Due to the heterogeneous nature of the vegetation in the Millingerwaard, results are worse than for a homogeneous grassland parcel at the Wageningen site.

4. CONCLUSIONS

Results presented in this paper show that the spectral derivative for wavelengths on the slopes of the water absorption features at 970 nm and 1200 nm can be used for estimating canopy water content (CWC). Model simulations show a good relationship between the derivative at 942.5 nm and CWC, which is not very sensitive for leaf and canopy structure. In addition the influence of sun-viewing geometry seems to be minimal. Field spectroscopic measurements on plots in a homogeneous grassland parcel confirm these results. For a nature area with many different plant species, results were less good, but still results show the potential of the derivative of the spectral reflectance at the shoulders of the mentioned water absorption features. The relationship between derivative and CWC based on the real spectral measurements obtained in the field appears to match the simulated relationship at the same spectral position obtained from a combined PROSPECT-SAILH model. This shows that we may transfer simulated results to real measurements obtained in the field for various vegetation types. Of course, more research is required on this subject. This study clearly indicates that derivatives provide better results in estimating canopy water content than reflectances or indices as used in literature (Sims and Gamon, 2003). Moreover, this paper shows that results obtained at the leaf level can be upscaled to the canopy level using field spectroradiometers. Next step should be the upscaling to the regional level using airborne hyperspectral data.

In this paper we used the derivative at 942.5 nm for illustrating the potential of the derivative in estimating CWC. However, in this region of the electromagnetic spectrum one also has to take the influence of the atmosphere into account. Significant absorption due to water vapour in the atmosphere occurs at 940 nm and 1140 nm (Gao and Goetz, 1990; Iqbal, 1983). These atmospheric absorption features are at shorter wavelengths as compared to the liquid water absorption features in the plant material, meaning they are at the left shoulders of the plant water absorption features. Therefore, the derivative at the right shoulders of the absorption features will be more useful for practical applications because they are not influenced by atmospheric water vapour. Figure 12 shows results for the R^2

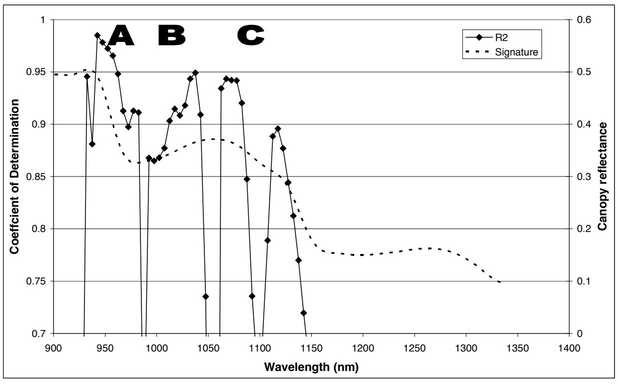

Figure 12. Coefficients of determination between canopy water content and first derivative of canopy reflectance. The dotted line provides an example of a canopy reflectance signature (PROSPECT-SAILH)

values of the derivatives over the 900 – 1300 nm region and the CWC for model simulations with the combined PROSPECT-SAILH radiative transfer model. Although R^2 values are highest at the left shoulder of the 970 nm absorption feature, derivatives at the right shoulder also provide high R^2 values. Therefore, for practical applications a derivative at about 1040 nm also seems to be feasible.

REFERENCES

Clevers, J.G.P.W. and L. Kooistra, 2006. Using spectral information at the NIR water absorption features to estimate canopy water content and biomass. *ISPRS mid-term symposium 2006 remote sensing: from pixels to processes*, 8-11 May 2006, Enschede, The Netherlands, pp. 6.

Curran, P.J., 1989. Remote sensing of foliar chemistry. *Remote Sensing of Environment*, 30(3), pp. 271-278.

Curran, P.J., J.L. Dungan and D.L. Peterson, 2001. Estimating the foliar biochemical concentration of leaves with reflectance spectrometry testing the Kokaly and Clark methodologies. *Remote Sensing of Environment*, 76(3), pp. 349-359.

Danson, F.M., M.D. Steven, T.J. Malthus and J.A. Clark, 1992. High-spectral resolution data for determining leaf water content. *International Journal of Remote Sensing*, 13(3), pp. 461-470.

Gao, B.C., 1996. NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3), pp. 257-266.

Gao, B.C. and A.F.H. Goetz, 1990. Column atmospheric water vapor and vegetation liquid water retrievals from airborne imaging spectrometer data. *Journal of Geophysical Research*, 95(D4), pp. 3549-3564.

Iqbal, M., 1983. *An introduction to solar radiation*. Academic Press, Ontario, 390 pp.

Jacquemoud, S. and F. Baret, 1990. Prospect - a model of leaf optical properties spectra. *Remote Sensing of Environment*, 34(2), pp. 75-91.

Kokaly, R.F. and R.N. Clark, 1999. Spectroscopic determination of leaf biochemistry using band-depth analysis of absorption features and stepwise multiple linear regression. *Remote Sensing of Environment*, 67(3), pp. 267-287.

Kuusk, A., 1991. The angular-distribution of reflectance and vegetation indexes in barley and clover canopies. *Remote Sensing of Environment*, 37(2), pp. 143-151.

Malenovský, Z., C. Ufer, Z. Lhotáková, J.G.P.W. Clevers, M.E. Schaepman, J. Albrechtová and P. Cudlín, 2006. A new hyperspectral index for chlorophyll estimation of a forest canopy: Area under curve normalised to maximal band depth between 650-725 nm. *EARSeL eProceedings*, 5(2), pp. 161-172.

Morisette, J.T., F. Baret, J.L. Privette, R.B. Myneni, J.E. Nickeson, S. Garrigues, N.V. Shabanov, M. Weiss, R.A. Fernandes, S.G. Leblanc, M. Kalacska, G.A. Sanchez-Azofeifa, M. Chubey, B. Rivard, P. Stenberg, M. Rautiainen, P. Voipio, T. Manninen, A.N. Pilant, T.E. Lewis, J.S. Iiames, R. Colombo, M. Meroni, L. Busetto, W.B. Cohen, D.P. Turner, E.D. Warner, G.W. Petersen, G. Seufert and R. Cook, 2006. Validation of global moderate-resolution LAI products: A framework proposed within the CEOS Land Product Validation subgroup. *Ieee Transactions on Geoscience and Remote Sensing*, 44(7), pp. 1804-1817.

Penuelas, J., I. Filella, C. Biel, L. Serrano and R. Save, 1993. The reflectance at the 950-970 nm region as an indicator of plant water status. *International Journal of Remote Sensing*, 14(10), pp. 1887-1905.

Running, S.W. and J.C. Coughlan, 1988. A general-model of forest ecosystem processes for regional applications .1. Hydrologic balance, canopy gas-exchange and primary production Processes. *Ecological Modelling*, 42(2), pp. 125-154.

Sims, D.A. and J.A. Gamon, 2003. Estimation of vegetation water content and photosynthetic tissue area from spectral reflectance: a comparison of indices based on liquid water and chlorophyll absorption features. *Remote Sensing of Environment*, 84(4), pp. 526-537.

Verhoef, W., 1984. Light scattering by leaf layers with application to canopy reflectance modeling: the SAIL model. *Remote Sensing of Environment*, 16(2), pp. 125-141.